

**HIGH POWER/WEIGHT RATIO BRAKING DEVICE BASED ON SHAPE
MEMORY MATERIAL TECHNOLOGY**

[0001] The invention relates to brakes.

[0002] When it comes to slowing down or completely stopping the rotation of a mechanical system, different braking strategies are being used. The most common brake technologies include viscous brakes, hydrodynamic brakes where a fluid is forced to pass through a flow restriction orifice, magnetorheological brakes where a particular fluid changes its viscosity under the application of a variable magnetic field, electromagnetic brakes where a force opposing the rotation of a system is set up by inducing eddy currents within a metal disc inserted between two electromagnets, and friction brakes where two surfaces are pressed one against the other.

[0003] There are many types of friction brakes, which are set apart by the shape of their friction surfaces and the nature of their activation principle. There are six main types of friction brakes, namely drum brakes, disc brakes, belt brakes, electromechanical and electromechanical power off brakes and magnetic particles brakes. Drum brakes consist of a cylindrical braking surface on to which one or more brake shoes are pressed when the brakes are activated. Friction of the shoe on the drum surface slows down the rotation of the system. Disc brakes use a clamping action to produce friction between a disc and two pads mounted in a caliper. As the caliper pinches the disc with the pads, which are positioned on opposite sides of the disc, the rotation of the system is slowed down. Belt brakes consist of a friction belt wrapped around a drum. The tension in the belt is proportional to the gripping force between the belt and drum, thus increasing this tension slows down the rotation of the drum. All these friction brakes may either be hydraulically, pneumatically or electrically activated as long as the selected

1 activation principle ensures adequate functioning of the mobile brake element
2 (shoe, pads or belt).

3 **[0004]** Electromechanical brakes operate via an electric actuation, but
4 transmit torque mechanically. When voltage is applied to the brake, a coil is
5 energized creating a magnetic field, which turns the coil into an electromagnet.
6 The resulting magnetic flux attracts an armature that is brought into contact with
7 friction pads. Since the armature is fixed relative to the shaft and the pads are
8 fixed relative to the frame, activation of the brake slows down the rotation of the
9 system. In most designs, springs hold the armature away from the brake surface
10 when power is released. Conversely, in some designs, a series of springs force
11 the armature in contact with the brake surface when no power is applied to it.
12 These brakes, called electromechanical power off brakes, are released by
13 applying voltage to a coil, which pushes the armature away from the brake
14 surface.

15 **[0005]** In magnetic particle brakes, magnetic particles are located in a cavity
16 where they simply lay when no power is applied. However, as soon as voltage is
17 applied to a coil located on top of the cavity, the magnetic flux created tends to
18 bind the particles together. As the voltage is increased, binding of the particles
19 becomes stronger. Since the brake rotor passes through these bounded particles,
20 the resistance force created on the rotor slows down the rotation of the system.

21 **[0006]** In the field of prosthetics, several types of brakes have been used in
22 the past to control relative pivotal movement between components of the
23 prosthesis, each having their benefits and drawbacks.

24 **[0007]** Viscous brakes are well suited for prosthetic applications but are
25 subject to leakage and failure under high loading conditions. Moreover, their
26 relatively high weight makes them less interesting compared to other solutions.

1 [0008] Magnetorheological fluids are theoretically suitable for applications
2 where the viscosity of the braking device needs to be rapidly and accurately
3 modified. However, practical applications have shown that this change in viscosity
4 is not rapid and accurate enough to achieve acceptable performances in the field
5 of prosthetics. Moreover, as with the viscous brakes, their relatively high weight is
6 detrimental to their selection in applications where dynamic braking is not a
7 requirement.

8 [0009] Friction brakes are not recommended for dynamic braking
9 applications since the friction coefficient of the contact surfaces tends to change
10 after extended use. However, their simplicity, compactness and lightness make
11 them an interesting choice whenever dynamic braking is not necessary.

12 [0010] Furthermore, all braking devices presented above have a common
13 limitation in that they require power to remain activated or inactivated.

14 [0011] Accordingly, it is an object of the present application to obviate or
15 mitigate some or all of the above disadvantages.

16 SUMMARY

17 [0012] According to one aspect of the present invention, there is provided a
18 friction brake assembly to act between a pair of relatively moveable components
19 and comprising a braked member connected to one of said components, a carrier
20 connected to the other of said components and a friction pad attached to the
21 carrier for engagement with the brake member. A first actuator is operable upon
22 the carrier to move the friction pad into engagement with the brake member. A
23 second actuator is operable upon the carrier to move the friction pad away from
24 the brake member. A control operates selectively on the first and second
25 actuators.

1 **[0013]** According to a further aspect of the present invention, there is
2 provided a prosthesis having a pair of limbs pivotally connected on one another by
3 a mechanical joint. An actuator is connected between the limbs to effect relative
4 rotation there between and a brake acts to inhibit such relative motion. The brake
5 is operative upon the actuator to inhibit further movement in the joint.

6 **[0014]** The braking device exhibits the ability to maintain a given state of
7 activation when no power is supplied to it. The preferred embodiment of this
8 device takes advantage of some particular characteristic of shape memory alloys
9 (SMA), namely the shape memory effect. The preferred embodiment of brake may
10 be packaged on a leg prosthesis for above knee amputees but is not restricted to
11 this specific application. It suits any general application where a braking action
12 needs to be applied between a pair of components.

13 **[0015]** In the preferred embodiment, actuation of the brake is provided a set
14 of shape memory alloy (SMA) wires positioned, in an agonistic-antagonistic
15 configuration on each side of a brake lever. Braking and releasing phases are
16 dictated by the austenitic transformation of the SMA wires by the application of an
17 electrical current to shorten one set of wires. During brake activation, shrinking of
18 the braking wires brings the friction pad in contact with a rotating drum creating a
19 braking friction torque. Once the brake has been activated, deformation of a
20 flexible component prevents the releasing of the brake by maintaining sufficient
21 normal force between the drum and the friction pad. Conversely, upon activation
22 of the releasing wires, the pad loses its grip and the drum is free to rotate.

23 **[0016]** Half of the SMA wires are used for brake activation while the other
24 half is used for brake release. Braking amplification factor is determined by the
25 position of the lever pivot. Aluminum 6061-T6 is well suited as a bulk material for
26 weight reduction purposes. In order to increase the brake coefficient of friction,
27 aluminum-bronze and steel are used for braking pad and drum manufacturing

1 respectively. It is estimated that a 5V – 50A power supply is suitable for brake
2 activation and release according to the SMA specifications.

3 **[0017]** Other features and advantages of the present invention will be more
4 readily apparent from the following detailed description, which proceeds with
5 reference to the accompanying figures.

6 **[0018]** Figure 1 is a perspective view of a prosthesis incorporating a braking
7 system.

8 **[0019]** Figure 2 is a perspective view on an enlarged scale of the braking
9 system utilized in Figure 1.

10 **[0020]** Figure 3 is a further perspective view of the assembled components
11 of the braking system shown in Figure 2.

12 **[0021]** Figure 4 is an exploded view of the components of the braking
13 system shown in Figure 1.

14 **[0022]** Figure 5 is a free body diagram of the brake in an activated state.

15 **[0023]** Figure 6 is a deformation analysis of a component utilized in the
16 brake shown in Figure 2.

17 **[0024]** Figure 7 is a trigometric analysis of a brake pad displacement for the
18 brake shown in Figure 2.

19 **[0025]** Figure 8 is a free body diagram of the components shown in Figure
20 6, and

21 **[0026]** Figure 9 is a free body diagram similar to Figure 8 in a different mode
22 of operation.

1 **[0027]** The braking system has been developed in the context of a
2 prosthesis for an above knee amputee and therefore will be described within that
3 context to illustrate the particular attributes of the system to this field of endeavor.
4 However, it will be understood that the braking system is more generally
5 applicable.

6 **[0028]** Referring therefore to Figure 1, a powered prosthesis 10 has a knee
7 joint assembly 12 connected between a lower limb 14 and a socket 18. The knee
8 joint assembly 12 permits relative rotation between the socket 18 and the lower
9 limb 14 which in turn is connected to a foot 15 through a cantilevered support
10 beam 20. Rotation of the knee joint 12 is controlled by an actuator 16 pivotally
11 connected, as indicated at 22, to the lower limb assembly 14 and at its opposite
12 end to bifurcated arms 24 forming part of the knee joint assembly 12. The actuator
13 16 is a screw type actuator with an armature rotatable within the outer casing and
14 engaged through a screw thread with a linearly displaceable output shaft 26.
15 Rotation of the armature induces longitudinal displacement of the shaft 26 causing
16 the actuator 16 to lengthen or shorten and cause a corresponding rotation in the
17 knee joint assembly 12. Further details of the actuator and knee joint assembly
18 may be found from the Applicants corresponding PCT Application PCT/ and
19 accordingly further description is not required at this time. In order to inhibit
20 rotation of the knee joint assembly 12, a brake assembly 28 is incorporated on the
21 actuator 16, and is operable to inhibit changes in the length of the actuator 16
22 when engaged. The details of the brake assembly 28 are more readily seen in
23 Figures 2, 3 and 4.

24 **[0029]** Referring therefore to Figure 2, the actuator 16 has an outer housing
25 29 with an end cap 30. An armature is rotatably mounted within the housing 29
26 and is rotatably supported in the end cap 30 on a boss 32 that projects through the
27 end cap 30. The actuator shaft 26 extends through the boss 32 and is
28 displaceable longitudinally upon rotation of the armature by virtue of the screw

1 threaded connection between the armature and the shaft 26. Rotation of the shaft
2 26 is inhibited by its connection to the ears 24.

3 **[0030]** The boss 32 has a brake drum 40 secured to it for rotation with the
4 boss 32. A brake shoe carrier 42 is pivotally connected through a pin 44 to a
5 mounting block 46 that projects from the body 29 of actuator 16. The carrier 42
6 acts as a lever and is formed as a semi-cylindrical cup having outer flanges 48
7 between which is secured a part cylindrical brake shoe 50. The brake shoe 50 is
8 configured to conform to the outer surface of the brake drum 40 and frictionally
9 engage the brake drum.

10 **[0031]** The opposite end of the carrier 42 to the pin 44 is connected to a
11 beam 52 that projects radially between a pair of ears 54. The beam 52 is made
12 from electronically non-conductive material and is designed to provide a controlled
13 flexure upon application of a braking force as will be described below.

14 **[0032]** The ears 54 are secured to the body 28 of the actuator 16 and
15 project axially to the extent of the brake assembly 28. Each of the ears 54 has an
16 axial slot 56 to accommodate a set of shape memory alloy (SMA) rods 58. The
17 rods are secured to a mounting block 60 which is pivotally secured by a trunnion
18 62 to the ears 54. The opposite ends of the rods 58 are received in respective
19 sets of holes 64 formed in the beam 52. The rods 58 are secured to the beam 52
20 through terminal blocks 66, 68 which permits adjustment of the rods to ensure
21 correct positioning of the shoe 50 relative to the drum 40.

22 **[0033]** The rods 58 are formed from a shape memory alloy, such as that
23 available under the trademark Nitinol. The rods 58 are pre-stressed and shape
24 memory alloy has the characteristic that a current applied to the rods 58 induces
25 an austenitic transformation causing a shortening of the rods 58. Upon removal of

1 the current, the length of the rods 58 remains unchanged until a further current is
2 applied.

3 **[0034]** The rods 58 are secured to the mounting block 60 through terminal
4 blocks 70, 72 in a manner similar to the terminal blocks 66, 68. The terminal block
5 70 engages a single rod 58 and has a conductor 74 connected to it. The terminal
6 block 72 is connected to a pair of rods 58 and thus electrically connects the two
7 rods to one another. The arrangement of blocks 70, 72 at both the ears 54 and
8 the terminal blocks 66, 68 on beam 52 is such as to serially connect the rods 58 of
9 each set in an electrical circuit and thereby ensure the same current is applied to
10 each. The conductors 74 are connected to appropriate control circuit responsive
11 to a control signal to apply or release the brake assembly 28.

12 **[0035]** In operation, the rods 58 are adjusted such that the carrier 42
13 maintains the shoe 50 in slight rubbing contact or minimal clearance with the drum
14 50 with no current supplied to the rods. In this condition, the actuator 16 is
15 operable to rotate the armature and cause longitudinal displacement of the shaft
16 26 to effect rotation about the knee joint assembly. Rotation of the armature is
17 controlled through suitable control functions as described in the above mentioned
18 published PCT application.

19 **[0036]** When braking is required, rotation of the armature is inhibited to
20 maintain the rod 26 in a fixed position by supplying a current through the conductor
21 74 to one of the sets of rods 58. The rods 58 of that set shorten upon application,
22 upon passage of the current and thereby act through beam 52 to cause pivotal
23 movement of the carrier 42 about the pin 44. This brings the shoe 50 into
24 engagement with the outer surface of the drum 40 and applies a retarding force on
25 the drum. The current supplied through the conductor 74 is terminated and the
26 rods 58 maintain substantially their decreased length to hold the shoe in contact
27 with the drum.

1 **[0037]** The application of force from the rods 58 through the beam 52
2 causes a flexure of the beam in proportion to the load applied. Upon removal of
3 the current to the conductors 74, the deflection in the beam 52 is used as a bias to
4 load the shoe 50 against the drum 40 through the intermediary of the carrier 42
5 and thereby maintain the braking force at the required level.

6 **[0038]** In order to release the brake, current is directed to the other set of
7 rods 58 causing them to shorten and release the load on the carrier 42. Thus, by
8 selectively applying the current to one or other of the set of rods, braking and
9 release can be effected and the brake maintained in a stable position without the
10 continued application of electrical power. During actuation, either to brake or
11 release a current is supplied to one set of rods 58 but not the other. The force
12 generated by the set to which current is supplied is much greater than that
13 necessary to extend the other set over the limited range of motion required,
14 ensuring effect actuation of the brake assembly 28.

15 **[0039]** In general, the brake assembly 28 may be adapted to any application
16 where a braking torque needs to be either applied to or released from a
17 mechanical system in rotation, even when no power is supplied to it. The brake
18 requires power input only to change its state from activated to inactivated and vice-
19 versa. The brake operation has been described by way of a particular
20 embodiment describing an example application in which the brake assembly
21 provides emergency braking on a motorized prosthesis in case of power failure
22 and power shut down. The embodiment achieves this by taking advantage of
23 some particular characteristic of shape memory alloys (SMA), namely the shape
24 memory effect. A typical set of criteria to be fulfilled in this example application
25 requires the brake to:

26 **[0040]** 1. Be active at power failure or shut down, i.e. the brake remains in
27 position after activation or release even if no power is supplied to it.

1 **[0041]** 2. Withstand static load of the amputee when standing on one leg,
2 i.e. the brake produces a minimal torque of 2.2Nm when activated.

3 **[0042]** 3. Completely blocks the prosthesis as quickly as possible, i.e. the
4 brake blocks the prosthesis in less than 100ms and may be released in less than
5 2s.

6 **[0043]** 4. Be electrically activated, i.e. the brake may be adapted to a
7 commercially available power supply.

8 **[0044]** 5. Respects specific security constraints, i.e. the brake operates in a
9 temperature range defined between -20°C and 40°C , the temperature of the SMA
10 elements never exceeding 150°C and brake lifespan is 100 000 cycles or better.

11 **[0045]** 6. Respects specific mass and volume constraints, i.e. the brake,
12 excluding the power supply, not weighing over 500g and not exceeding the
13 approximate volume of a 60mm-diameter and 60mm-long cylinder.

14 **[0046]** Using the general arrangement described above, the components
15 may be dimensioned to meet these requirements in the context of a prosthesis.
16 Suitable scaling may be applied to other environments.

17 **[0047] BRAKING DRUM**

18 **[0048]** Drum rotational inertia is a major concern since it affects the
19 dynamics of the prosthesis. In order to keep this parameter as low as possible,
20 the boss 32 maximal diameter is fixed to 23mm and the recommended material is
21 aluminum 6061-T6. In order to improve the coefficient of friction between the boss
22 32 and the friction pad 50, a 1mm-thick steel brake drum 40 is press-fitted onto the
23 boss 32.

24 **[0049] FRICTION PAD**

1 [0050] In order to get high friction coefficient and high heat dissipation
 2 properties, aluminum-bronze is preferably used as raw material for the friction pad
 3 50. Static coefficient of friction between aluminum-bronze and steel is estimated
 4 to 0.3. Considering this value and the short-shoe friction brake illustrated in FIG. 5
 5 and defined by Equation 1, the normal force between the braking drum 32 and
 6 friction pad 50 needs to provide a 2.2Nm braking torque on a 25mm diameter
 7 drum is estimated to 587N.

$$8 \quad N = \frac{T}{\mu r} \quad \text{Equation 1}$$

9 [0051] BRAKE LEVER

10 [0052] The brake amplification factor is directly related to the position of the
 11 lever pivot point. Considering the recommended stress applied to Nitinol® wires in
 12 martensitic state (20MPa), the cross-sectional area A of those wires (0.78mm²)
 13 and the normal force estimated above (587N), the amplification factor of the brake
 14 is evaluated to $X = 12.5$.

15 [0053] Equation 2, Equation 3 and Equation 4 are obtained from FIG. 5.
 16 Substituting Equation 2 and Equation 3 in Equation 4 and solving for a, the
 17 position of the pivot point is estimated to $a = 13\text{mm}$ and $b = 11\text{mm}$.

$$18 \quad X = \frac{(c^2 + d^2)^{1/2}}{b - \mu(a + r)} \quad \text{Equation 2}$$

$$19 \quad L^2 = c^2 + d^2 \quad \text{Equation 3}$$

$$20 \quad R^2 = a^2 + b^2 \quad \text{Equation 4}$$

21 [0054] For weight reduction purposes, aluminum 6061-T6 is recommended
 22 as the bulk material for the manufacturing of the carrier 42.

1 [0055] BEAM

2 [0056] The beam 52 is made of a material which has a low Young's
 3 modulus/Tensile strength ratio, for example fiberglass such as S-Glass-Epoxy.
 4 From FIG. 6 and Equation 5 and considering the properties of this material ($E =$
 5 45GPa and $S_u = 1000\text{MPa}$), a recommended flexural stress $\sigma_{\max} = 300\text{MPa}$, a
 6 maximal force at the extremity of the beam 52 $F = N/X = 46.9\text{N}$ and a 10mm-long
 7 and 10mm-wide beam 52, the minimal beam thickness is estimated to $h_{\min} = 1\text{mm}$.
 8 From FIG. 6 and Equation 6 and considering the same parameters, the deflection
 9 of the beam extremity is estimated to $\Delta_{DD1} = 0.42\text{mm}$.

$$10 \quad h_{\min} = \sqrt{\frac{6FW}{b\sigma_{\max}}} \quad \text{Equation 5}$$

$$11 \quad \Delta_{DD1} = \frac{4FW^3}{Eb h^3} \quad \text{Equation 6}$$

12 [0057] SMA ELEMENTS

13 [0058] The length of the SMA elements (12, 21) may be obtained from
 14 Equation 7, where the active strain of the braking SMA elements (21) is $\varepsilon_a = 4\%$,
 15 the elastic recovery strain of the releasing SMA elements (12), under the
 16 application of a force $F = 46.9\text{N}$, is $\varepsilon_{\text{rec}} = 0.07\%$ while the strain of the braking SMA
 17 elements 58 under the same force is $\varepsilon = 0.5\%$. Obtaining the displacement of
 18 brake carrier 42 extremity DD' from FIG. 7 and the deflection of the beam 52
 19 extremity from Equation 6, the length of the SMA elements 58 is evaluated to be
 20 $L_{\text{SMA}} = 30\text{mm}$.

$$21 \quad \varepsilon_a L_{\text{SMA}} = DD' + \varepsilon_{\text{rec}} L_{\text{SMA}} + \Delta_{DD1} + \varepsilon L_{\text{SMA}} \quad \text{Equation 7}$$

1 **[0059]** Considering Equation 8, the volume of each SMA elements 58 is
 2 estimated to be $V = 23.4\text{mm}^3$ ($0.78\text{mm}^2 \times 30\text{mm}$), that is the total volume of the
 3 three braking SMA elements 58 as well as the three releasing SMA elements 58 is
 4 $V_{\text{TOT}} = 70.2\text{mm}^3$ ($3 \times 23.4\text{mm}^3$). From Equation 9 and considering the density of
 5 Nitinol®, $\rho = 6450\text{kg/m}^3$, the mass of each SMA elements 58 is estimated to be m
 6 $= 1.51 \times 10^{-4}\text{kg}$, that is the total mass of the three braking SMA elements 58 as well
 7 as the three releasing SMA elements 58 is $m_{\text{TOT}} = 4.53 \times 10^{-4}\text{kg}$ ($3 \times 1.51 \times 10^{-4}\text{kg}$).
 8 Finally, from Equation 10 and considering the electrical resistivity of Nitinol®, $\rho_{\text{el}} =$
 9 $0.8\mu\Omega\text{m}$ and the three parallel SMA elements 58 on each side of the beam 52
 10 connected in series via steel blocks 66, 68, 70, 72. The electrical resistance of
 11 SMA elements 58 is estimated to be $R_{\text{el}} = 0.092\Omega$.

12 $V = AL$ Equation 8

13 $m = \rho V$ Equation 9

14 $R_{\text{el}} = \rho_{\text{el}} \frac{3L}{A}$ Equation 10

15 **[0060]** Stress generated by the braking SMA elements 58 during brake
 16 activation is obtained from FIG. 8 and Equation 11. Considering $F = 15.6\text{N}$, $W =$
 17 10mm , $x = 6\text{mm}$, $A = 0.78\text{mm}^2$ and $\sigma_m = 100\text{MPa}$, this parameter is estimated to
 18 be $\sigma_g = 80\text{MPa}$. From Equation 12 and considering room temperature, $T_{\text{amb}} =$
 19 25°C , Nitinol® transformation temperature, $A_s = 70^\circ\text{C}$, Nitinol® stress gradient
 20 $d\sigma/dT = 5\text{MPa}/^\circ\text{C}$ and the value of σ_g estimated above, total temperature elevation
 21 for brake activation is estimated to $\Delta T = 61^\circ\text{C}$.

22 $\sigma_g = \frac{FW + \sigma_m Ax}{AW}$ Equation 11

$$\Delta T = \frac{1}{\sigma_g} \frac{d\sigma}{dT} + (A_s - T_{amb}) \quad \text{Equation 12}$$

[0061] In a similar way, stress generated by the releasing SMA elements (12) during brake release is obtained from FIG. 9 and Equation 13. In this case, σ_g is estimated to 167MPa and the associated total SMA temperature elevation is estimated to $\Delta T = 78^\circ\text{C}$.

$$\sigma_g = \frac{\sigma_m x}{W} \quad \text{Equation 13}$$

[0062] The energy required for brake activation or release is obtained from Equation 14. Considering the latent heat and transformation enthalpy of Nitinol®, $c_p = 322\text{J/kg}^\circ\text{C}$ and $h_T = 24200\text{J/kg}$, the mass of material, $m = 4.53 \times 10^{-4}\text{kg}$ and the temperature elevation values stated above, the energy associated with brake activation is, $U_{act} = 19.9\text{J}$, whereas the energy associated with brake release is, $U_{rel} = 22.3\text{J}$.

$$U = m(c_p \Delta T + h_T) \quad \text{Equation 14}$$

[0063] From Equation 15, considering the parameters evaluated above and the SMA brake functional requirements, the current required to activate the brake in less than 100ms is estimated to $I_{act} = 46.5\text{A}$ whereas the current required to release the brake in less than 2s is estimated to $I_{rel} = 11\text{A}$. From Equation 16 and considering the current values evaluated above, the voltage associated with brake activation is estimated to $V_{act} = 4.3\text{V}$ whereas the voltage associated with brake release is estimated to $V_{rel} = 1\text{V}$.

$$I = \sqrt{\frac{U}{Rt}} \quad \text{Equation 15}$$

1 $V = RI$

Equation 16

2 **[0064] FRAME**

3 **[0065]** Components that remain fixed relative to the prosthesis, are
4 considered part of the frame. Those components are: the SMA inserts 60, the
5 trunnion blocks 62 and the lever pivot shaft 44. The SMA inserts 60 are made of,
6 for example, HST II phenolic, a relatively rigid electrical insulator. The trunnion
7 blocks are made, for example, of steel and are used to adjust the initial tension in
8 the SMA elements 58. The lever pivot shaft 44 is made of, for example, steel and
9 is positioned in such a way that the amplification factor of the brake is fixed to $X =$
10 12.5.

11 **[0066]** Although the present invention has been described by way of a
12 particular embodiment thereof, it should be noted that modifications may be
13 applied to the present particular embodiment without departing from the scope of
14 the present invention.